FINITE ELEMENT MODELING OF EDDY CURRENT TESTING OF STEAM GENERATOR TUBE WITH CRACK AND DEPOSIT

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INTRODUCTION

Eddy current testing (ECT) is a type of non-destructive testing and effective for detecting surface cracks or flaws in conducting materials. A typical application of the ECT is non-destructive testing for heat exchanger tubes of steam generators (SG) of chemical plants and nuclear power plants. Higher accuracy is needed for external very small cracks from the practical point of view. Recently there are some requests not only for the location of cracks but also for the characterization of crack shape and the type of cracks. In order to improve the accuracy of the ECT it is considered to be important to use numerical analysis and to optimize the method of testing and the shape of probe coils. Since the electromagnetic phenomena in the ECT are 3D in nature, 3D numerical analysis is required in order to know eddy current distribution in the conductor and to improve the ECT technique. Therefore one of recent research interests of the ECT is the development of more effective and accurate 3D eddy current analysis.

In SG tubes of a PWR type nuclear plant, it has been required that surface cracks, especially, outer cracks must be detected before they grow up. Here, a difficulty encountered is the processing of noised ECT signals. The noises may be caused by the variation of the lift-off of a probe, the presence of structures outside tubes, etc. It is

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difficult to judge whether cracks exist or not from the raw signals including these noises. Signal processing method by multi-frequency technique is often used. In older nuclear power plants, some deposits are sometimes formed on the outer surface of tubes. These deposits are composed of copper and magnetite for the most part, and are one of the causes of noise in ECT because of the electromagnetic nature of the test. In the case of the copper deposits, it is difficult to detect the cracks accurately even if signal processing technique is used.

In 1991 the Research Committee on the Integration of Eddy Current Testing was established in the Japan Society of Applied Electromagnetics and Mechanics, and had been discussing on the ECT both from numerical and experimental points of view. In the committee they discussed benchmark models with different levels of difficulty for the ECT of SG tubes, to verify several numerical codes, and to allow comparisons among these codes. In this paper we present finite element modelings of eddy current testing of SG tubes with cracks. The modellings and results described here are; 1) minute crack, 2)fatigue crack, and 3) crack with copper deposit.

EVALUATION OF SIGNAL DUE TO MINUTE CRACK

Evaluation Model

In order to discuss the signal of a minute crack by measurement and numerical analysis, we fabricated a sensor coil and a test piece illustrated in Figure 1[1]. A sham crack, that is not natural but is electrically perfect barrier, was made by the process of electric discharge machining (EDM) in a test piece. The coil has the same dimension as one of 8 ×1 pancake type probe which is used in the SG tube inspection of a PWR plant.

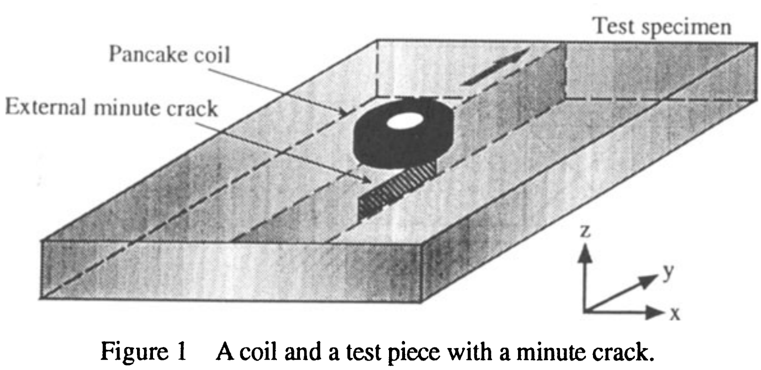


Figure 1 A coil and a test piece with a minute crack.

Its outer diameter, inner diameter and height are 3.2 mm, 1.6 mm and 0.8 mm. The coil has an axisymmetric shape with 140 turns. The test piece is made of Inconel 600: same material as a real SG tube for the PWR plant. The dimension of a test piece is 140 mm $\times$ 140 mm $\times$ 1.25 mmt. Relative permeability and conductivity are 1.0 and 1.0×10^6 S/m. The crack is located in the center of the test piece and the opposite side of the coil. We call this "Outer Defect (OD)" here. The length, width and depth of the crack are 10 mm, 0.2 mm and 20% to the plate thickness, respectively. Applied current to the coil is 1/140 A. Test frequencies are 150 kHz and 300 kHz. Lift-off, distance between the bottom of the coil and the surface of the test piece, is 0.5 mm.

The measurement system consists of a 3D stage and an impedance analyzer by which signal is taken[2]. The crack center is defined as y = 0 mm. This means that the location of a crack edge is y = 5 mm. The impedance is measured from the center, y= 0 mm, till y= 10 mm at every 1 mm. The impedance change over 10^{-3} % of total impedance of the coil can be measured by the impedance analyzer with strict calibration.

Numerical Analysis

In the numerical analysis of an ECT signal, it is important to calculate magnetic field with eddy current. The A-ϕ method, whose variables are magnetic vector potential A and electric scalar potential ϕ, is a popular and conventional method to calculate magnetic field with eddy current. The governing equations of the A-ϕ method on an AC problem in quasi-stationary state are shown as follows:

$$\frac{1}{\mu_o}\nabla^2\mathbf{A} = -\mathbf{J}_s + \sigma(j\omega\mathbf{A} + \nabla\phi) \tag{1}$$

$$\nabla\cdot\sigma(j\omega\mathbf{A} + \nabla\phi) = 0 \tag{2}$$

where, $\mathbf{J}_s$: source current density, j : imaginary unit, ω : angular frequency of AC current, μ_o : permeability of air, σ : conductivity. In this paper we assume the Coulomb gauge to obtain (1) and do not explicitly impose the gauge in nodal FEM formulation. Applied current was formulated as a constant AC current source in air. We used first order hexahedral elements to divide an analytical domain.

The impedance change $\mathbf{Z}_e$ of a coil due to eddy current can be given as,

$$\mathbf{Z}_e = \frac{-j\omega N_t \oint \mathbf{A}_e dl}{I} \tag{3}$$

where N_t and A_e are the number of coil turns and magnetic vector potential due to eddy current. A_e is obtained using Biot-Savart law. This is effective to reduce the errors from mesh division for a coil part. The solution obtained by solving (3) dose not include resistance of the windings and capacitance of a coil because the conductivity of the coil is assumed to be zero.

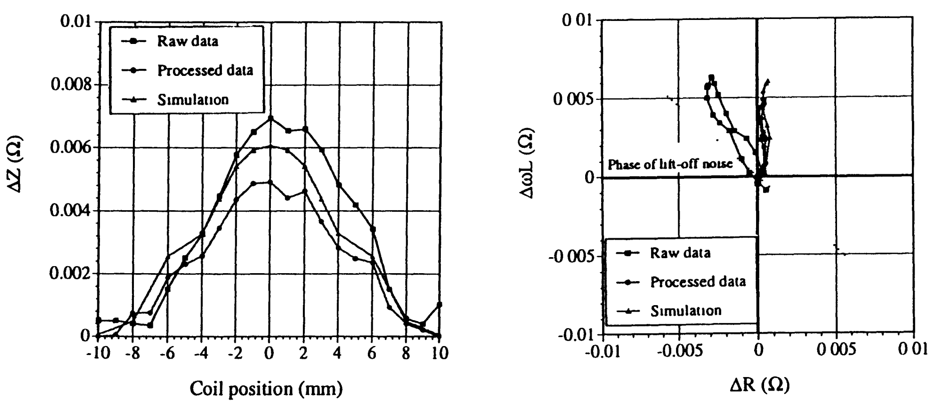
Results and Discussion

Very accurate solution and measurement data are necessary in order to evaluate the external minute crack in the ECT. This is because the signal due to a external crack (OD40% as referred in [2]) is recognized less than 0.1% of the total coil impedance. Therefore proper parameters in FEM, such as mesh division, convergence criteria in ICCG method, etc., must be carefully selected. We evaluated these parameters using the maximum value of the signal. The effects of mesh division and ICCG convergence criteria on the accuracy were evaluated. From these results, the parameters in the computation of eddy current and ECT signal should be optimized for the accurate evaluation. The parameters were consequently decided as shown in Table I.

Table I Parameters used in numerical analysis.

The number of total elements[a] (first order isoparametric element)	10368 (conductor 4046)
The number of total nodes[a]	11951 (conductor 5040)
The sampling points for Gauss-Legendre quadrature in a element	5×5×5
The convergence criteria of ICCG method	10^{-7}
The sampling points for the integral along a coil[b]	5×18×5

[a]1/2 symmetry
[b]1/2 symmetry, $r \times \theta \times z$ direction



(a) Impedance change (b) Impedance trajectory

Figure 2 Comparison of measurement and analysis for f=150kHz, OD 20%.

The results of measurement and simulation for OD20% are plotted in Figure 2. In the experiment, the impedance at every 1 mm was measured from y= -15 mm to y = 15 mm. Both in measurement and simulation, the impedance changes from the value at y = 10 mm are shown here. In the figure, difference exists between raw data and simulation. The signal from y = -10 mm to zero and from zero to y = 10 mm must follow the same trajectory. Moreover the phase of trajectory in the raw data was rotated in direction of the noise signal due to lift-off. We interpreted this error as the influence of very small deformation of the test piece caused by EDM. The processed data represents noise eliminated results from the raw data. The modified data and simulation results show good agreement.

FATIGUE CRACK

Evaluation Model and Experiment

The shape and sizes of tube were shown in Figure 3[3]. The initial crack was produced by EDM and after that a fatigue crack was made using a fatigue testing machine. The direction of the crack is circumferential on the outer surface of the tube. The depth of the EDM slit is 0.13 mm (10%), the length 10 mm and the width 0.12 mm. The depth, the length and the width of the fatigue crack are 0.37 mm (29%), 10 mm and 0.002 mm, respectively. The total depth of the crack is 0.50 mm (39%), respectively.

The impedance signals by the crack were measured using a pancake type coil explained in a previous section[2, 3]. The lift-off was 0.5 mm. The testing frequency was 300 kHz. The fatigue crack had been measured by an eddy current testing equipment used in real SG tubes. Because the impedance change by the fatigue crack could not be obtained directly, it was estimated comparing the ECT signal of the fatigue crack with an outer EDM crack of 40%.

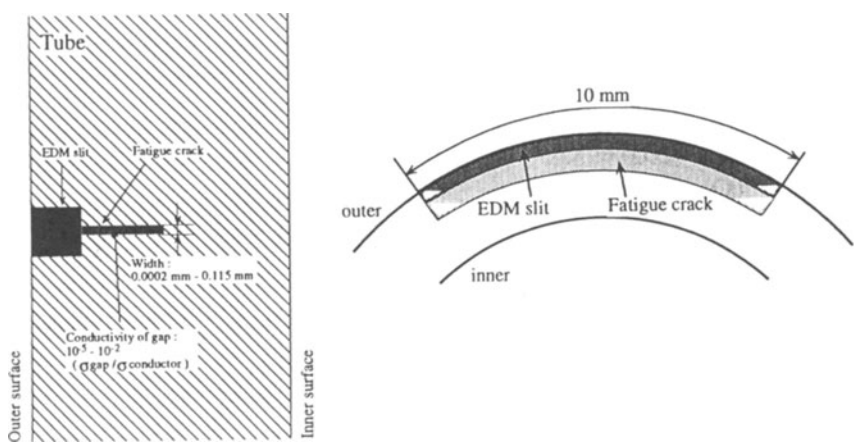


Figure 3 Shape of a fatigue crack.

Results and Discussion

A numerical model of the fatigue crack is shown in Figure 4. We calculated the model with various sizes of crack width as shown in the figure. Next, we consider that there exist partial electric contacts at the crack surface. So we think that the gap of the crack has small electric conductivity for imitating partial contacts. Impedance change becomes smaller in proportion to the width of crack gap, and converges on a value when the width is shorter than 0.002 mm. The absolute value of the converged impedance change are larger than measured signal. Next, we evaluated conductivity change in the gap of the crack. After the impedance change converges with 0.002 mm gap, we change conductivity ratio from 10^{-5} to 10^{-2} for the crack gap of 0.002 mm. From these results, we understood that numerical analysis method which considered not only crack width but also conductivity of the gap is useful for the natural crack analysis.

COPPER DEPOSIT

Evaluation Model and Experiment

In order to discuss composite signal of a crack and a deposit by experiment and numerical simulation, a sensor coil, and a test piece with a copper sheet and a crack were fabricated as illustrated in Figure 5. A copper sheet simulates a copper deposit formed on the outer wall of the SG tubes. An artificial crack was made by the process of EDM in the test piece [3]. The crack and deposit were located in the center of the test piece and the opposite side of the coil. The centers of the crack and deposit were defined as x=0 mm and y= 0 mm. The location of a crack edge was located in y= 5 mm. Lift-off was 0.5 mm.

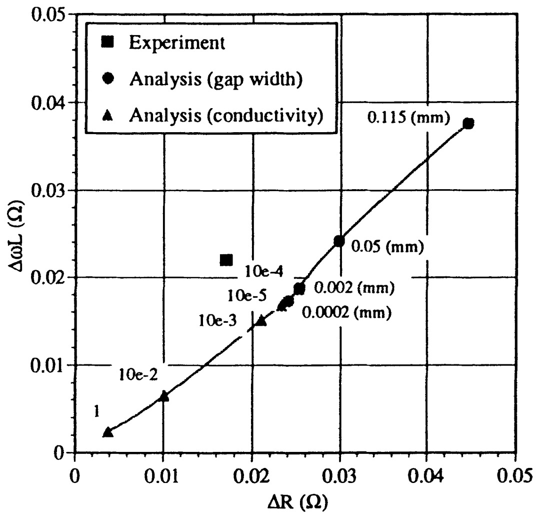


Figure 4 Comparison of measurement and analysis for a fatigue crack.

ECT Signal by Experiment and Simulation

Figure 6 shows the signals of 1D scanning at x= 0 mm by experiment and simulation in impedance plane. In simulation, as the test piece was larger than detecting area, only the crack region was moved without remeshing. The crack is OD60% and the thickness of a copper deposit is 0.08 mm. The simulation results show that the measurement are appropriate since these results agreed well.

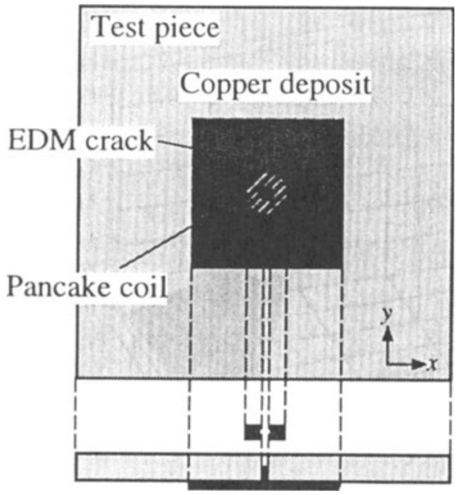


Figure 5 A coil and a test piece with a crack and a copper deposit.

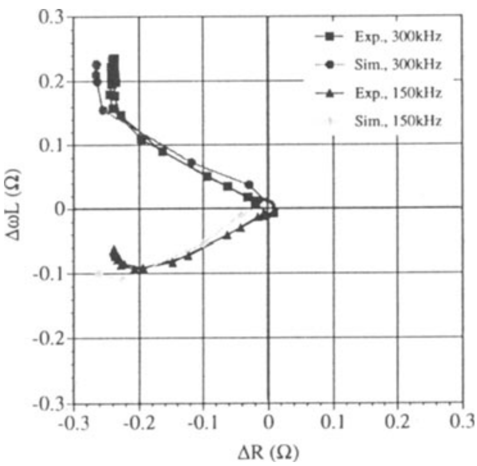


Figure 6 Comparison of measurement and numerical analysis for an OD 60% crack with a copper deposit.

SUMMARY

Finite element modeling and results of numerical analysis for eddy current testing of steam generator tubes with a crack were described in this paper. For three cases, 1) minute crack, 2) fatigue crack, and 3) crack with copper deposit, the comparison of numerical analysis and measurement were discussed. The results verified the accuracy of the modelings and the analysis method.

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